Direct Measurement of A_b in Z^0 Decays Using Charged Kaon Tagging

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We present a direct measurement of the parity-violating asymmetry A_b in the Z^0 to $b\overline{b}$ coupling using a new technique to distinguish the b and $\overline{b}$ quarks using charged kaons from B decays. The Z^0 bosons are produced in e^+e^- collisions at the SLC with longitudinally polarized electrons. $b\overline{b}$ events are selected using a secondary vertex mass tag and A_b is determined from the left-right forward-backward asymmetry. From the 1994–1995 data sample, selected from 100 000 hadronic Z^0 decays, we obtain $A_b = 0.855 \pm 0.088_{\text{stat}} \pm 0.102_{\text{syst}}$.

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The measurement of the Z^0 to b quark coupling asymmetry provides a precision test of the standard model (SM) of electroweak interactions which is especially interesting. Physics beyond the SM may couple more strongly to the third generation fermions, producing larger changes in b couplings than in other quark couplings. A variety of distinctive characteristics of the b hadron decays have also made these measurements particularly attractive experimentally. Parity violation in $Zb\overline{b}$ couplings can be expressed in terms of the combination of left-handed (g_L^b) and right-handed (g_R^b) couplings, as $A_b = [(g_L^b)^2 - (g_R^b)^2]/[(g_L^b)^2 + (g_R^b)^2]$. The measurement of A_b is particularly sensitive to possible deviations from the predicted right-handed coupling, complementary to the measurement of $R_b \equiv \Gamma(Z^0 \to b\overline{b})/\Gamma(Z^0 \to \text{hadrons})$ which is more sensitive to the left-handed coupling. With the availability of longitudinal electron beam polarization P_e, A_b can be measured directly from the left-right forward-backward asymmetry for $e^+e^- \to Z^0 \to b\overline{b}$ events,

$$\tilde{A}_{\text{FB}}^b(\cos\theta) = \frac{[\sigma_L^b(\cos\theta) - \sigma_L^b(-\cos\theta)] - [\sigma_R^b(\cos\theta) - \sigma_R^b(-\cos\theta)]}{[\sigma_L^b(\cos\theta) + \sigma_L^b(-\cos\theta)] + [\sigma_R^b(\cos\theta) + \sigma_R^b(-\cos\theta)]} = |P_e| A_b \frac{2\cos\theta}{1 + \cos^2\theta}, \tag{1}$$

where σ_L^b and σ_R^b are the cross sections of $Z^0 \to b\overline{b}$ decays produced with a predominantly left-handed (negative helicity) or right-handed (positive helicity) electron beam, respectively, and θ is the b quark production polar angle with respect to the electron beam direction. In contrast, the conventional forward-backward b asymmetry $A_{\text{FB}}^b = \frac{3}{4}A_e A_b$, as measured at LEP [1] with unpolarized beams, is a compound variable also sensitive to the initial state Zee coupling parameter A_e. A large value of $|P_e|$ from a highly polarized electron beam produces a raw asymmetry which is much larger than A_{FB}^b and so enhances sensitivity to A_b.

Direct measurements of A_b using left-right forward-backward asymmetries have been performed previously by SLD [2], in which the b and $\overline{b}$ quarks were distinguished using momentum weighted track charge or the charge of decay leptons. In this paper, we present the first application of a new technique for distinguishing b and $\overline{b}$ quarks using identified $K^\pm$ to an asymmetry measurement. This technique exploits the correlation between the kaon charge and the parent B flavor from the dominant $b \to c \to s$ cascade decay. This technique is expected to be one of the most powerful B flavor tagging tools for future B physics experiments. We demonstrate with this measurement that it can already be very effectively employed. The analysis procedure begins with a selection of $b\overline{b}$ events using the vertex detector. Tracks associated with the B decay vertex and identified as $K^\pm$ are used to distinguish b and $\overline{b}$ quarks. A fit to the left-right forward-backward asymmetry as a function of the event thrust $\cos\theta_{\mathrm{thrust}}$ determines A_b, using the Monte Carlo (MC) as a fitting function.

The operation of the SLAC Linear Collider (SLC) with a polarized electron beam has been described previously [3]. During the 1994–1995 running period, SLD recorded ~100 000 hadronic Z^0 decays at a mean center of mass energy of 91.28 GeV with an average longitudinal electron beam polarization of $77.2\% \pm 0.5\%$ [3]. Charged particle tracking is provided by the central drift chamber (CDC) and a CCD-based pixel vertex detector (VXD) within a uniform axial magnetic field of 0.6 T. The liquid argon calorimeter is used for the triggering and selection of the events, as well as for determination of the event thrust axis. A more detailed description of the above detector components, the tracking performance and the precision primary vertex determination procedure can be found in Ref. [4]. Central to this analysis is the identification of $K^{\pm}$ provided by the barrel Cherenkov Ring Imaging Detector (CRID) [5]. Using a combination of liquid and gaseous radiators, the CRID provides efficient K-π separation over the momentum range $0.3 < p < 30$ GeV/c, and K-p separation over the ranges $0.75 < p < 5$ and $9 < p < 50$ GeV/c for tracks within $|\cos\theta| < 0.67$.

Our MC simulation of $Z^0 \rightarrow$ hadrons uses the JETSET 7.4 [6] generator framework. The decays of charmed mesons and baryons are simulated according to measured branching ratios [7]. The B meson decay simulation is based on the QQ MC program from the CLEO collaboration. The B decay daughter momentum spectra in the B rest frame for leptons, charm mesons, $\pi^{\pm}, K^{\pm}, K^0$, and protons are tuned to closely reproduce the CLEO and ARGUS inclusive measurements [8,9]. The MC detector simulation is based on GEANT 3.21 [10].

Hadronic Z^0 decay events are selected [4] by requiring that the event total visible energy from charged tracks is >18 GeV and there are ≥7 CDC tracks. The event thrust axis is required to be within $|\cos\theta_{\mathrm{thrust}}| < 0.70$. The CDC, VXD, and CRID must all be in normal operation. A fiducial set of 54 638 Z^0 events is obtained from the 1994–1995 data. The corresponding sample of MC events is ≈172 000, plus an additional ≈163 000 $b\overline{b}$ only MC events.

A set of "quality tracks" is selected according to the criteria in [4] to tag $b\overline{b}$ events and to identify kaons. Particle identification (ID) information from the CRID liquid (gas) system is considered for quality tracks in the momentum range 1.3–9 (2.5–17) GeV/c that satisfy a set of "identifiability" criteria [11]. These criteria are typically specified separately for tracks with momentum above and below 2.5 GeV/c which corresponds roughly to the pion gas ring threshold. Tracks in the CRID fiducial volume typically produce a heavy ionization signal in the Cherenkov photon detector which can be used to ensure that the tracks are well reconstructed and did not terminate before reaching the CRID. Both π, K tracks at $P > 2.5$ GeV/c should also have liquid rings at an asymptotic radius which can also be used to ensure track quality for gas ring analysis. The actual criteria are the following: The track must extrapolate through an active region of the liquid (gaseous) radiator; at least 50% (80%) of the ring with asymptotic maximum radius at the expected location must be contained within an active region of a photon detector; if the track extrapolates through an active photon detector, there must be an ionization signal in that photon detector; for the gas ring analysis at $P > 2.5$ GeV/c, if the track does not extrapolate through an active photon detector, it must have at least four hits consistent with a liquid ring. For tracks with $2.5 < p < 9$ GeV/c, both liquid and gas information are required. Of the quality tracks in the fiducial volume of $|\cos\theta| < 0.67$, 74% are identifiable.

For each identifiable track, log-likelihoods $\mathcal{L}_i$ [5,12] are calculated for the pion, kaon, and proton hypotheses, combining liquid and gas information. A track is identified as a charged kaon if $\mathcal{L}_K - \mathcal{L}_\pi > 5(3)$ and $\mathcal{L}_K - \mathcal{L}_{\mathrm{p}} > -1$ for tracks in the momentum range 1.3–2.5 (2.5–17) GeV/c. The first cut is used to reject pions while the second cut is used to remove candidates more likely to be protons. The efficiency for correctly identifying a kaon which satisfies the above selection criteria is estimated to be 69% on average, roughly independent of momentum and $\cos\theta$. The MC efficiency is corrected [5,11] slightly using the measured proton and pion tracks from tagged Λ^0 and K_s^0 decays. The probability for misidentifying a pion as a kaon has also been measured from the K_s^0 data, and varies from 1.5% at low momentum to up to 10% at high momentum. We also checked from MC that the particle ID efficiency and mis-ID rates for these K_s^0 and Λ decay tracks are consistent with those for the prompt tracks used for the kaon-tag analysis. The background from misidentified protons is small and is estimated from the simulation. Overall, the kaon sample purity is 76%.

To isolate the kaons from B decays, $b\overline{b}$ events are tagged using the invariant mass of topologically reconstructed secondary vertices [13] at a distance >1 mm from the primary vertex. The tagging efficiency is enhanced by correcting the reconstructed vertex mass for missing transverse momentum, which partially accounts for neutral particles. The vertexing procedure is applied separately to the two hemispheres of each event which are defined by the plane perpendicular to the thrust axis. A sample of 7473 data events is selected after requiring the corrected vertex mass to be >1.8 GeV/c^2 in either hemisphere of an event, corresponding to a b-tag efficiency of 62% and a b purity of $96.0\% \pm 0.6\%$ derived from hemisphere tag and event double tag rates in the data. The background is mainly $c\overline{c}$ events. The B decay track candidates are then selected from hemispheres with a clearly separated secondary vertex, based on the longitudinal and transverse positions of the track at its 3D closest approach to the line between the secondary vertex and the primary vertex. The fraction of true B decay tracks among all selected track candidates is 97%.

The $K^{\pm}$ identification procedure is applied to the selected B decay tracks in the tagged hemispheres. The momentum distribution of the selected B decay kaon candidates is shown in Fig. 1, displaying good agreement between data and MC. The charges of the kaon candidates in each hemisphere are then summed. A negative (positive) kaon charge sum tags the b ($\overline{b}$) hemisphere. Events are rejected if both hemispheres have the same sign for the kaon charge sum. Multiple kaon candidates with zero net charge are found in 8.3 ± 0.5% of the hemispheres with kaon candidates, in agreement with the MC expectation of 8.3%. There are 2772 events in the data with successful kaon charge tags. The MC indicates that the b quark charge is correctly signed for $\langle p_{\mathrm{correct}} \rangle = 71.8\%$ of the selected $b\overline{b}$ events. A cross check is made using events with both hemispheres having kaon tags. The opposite sign fraction of 57.8% ± 3.1% in the data agrees with the MC value of 58.2% ± 0.8%.

The b quark production direction is approximated by the thrust direction and signed according to the observed kaon charge. Binned distributions of $\cos\theta_{\mathrm{thrust}}$ are formed for the left- and right-handed electron beam polarizations separately. The small $udsc$ background as estimated from the MC is subtracted to obtain the polar angle distribution for pure $b\overline{b}$ events. The left-right forward-backward asymmetry, $\tilde{A}_{\mathrm{FB}}^{\mathrm{meas}}(\cos\theta) = \alpha(\cos\theta)\tilde{A}_{\mathrm{FB}}^{b}(\cos\theta)$, is then formed according to Eq. (1) for both data and MC, where $\alpha(\cos\theta) = 2p_{\mathrm{correct}}(\cos\theta) - 1$ is the analyzing power of the kaon charge tag. The MC $\tilde{A}_{\mathrm{FB}}^{\mathrm{meas}}$ distribution is used as the fitting function in a χ^2 fit to the data. A $\cos\theta$-independent scaling factor is the only free parameter, and corresponds to the ratio between the A_b value in the data and the generated A_b value in the MC. The left-right forward-backward asymmetry distributions for the data and best fit MC are shown in Fig. 2. The fit χ^2 is 6.2/6.

The fitting procedure has effectively included the quantum chromodynamics (QCD) radiative corrections as generated in the JETSET MC, and has naturally taken into account any analysis bias to the QCD correction. In order to make the treatment of QCD corrections consistent with other direct measurements of A_b from SLD [2], which take the effect of b-quark mass into account at leading order [14], a correction of -0.5% is applied, resulting in a measurement of $A_b = 0.855 \pm 0.088_{\mathrm{stat}}$.

The systematic errors are summarized in Table I. Because of the formulation of the double asymmetry in $\tilde{A}_{\mathrm{FB}}$, many effects of detector nonuniformity cancel. Among the remaining detector systematic effects, the uncertainties in $\pi \rightarrow K$ mis-ID rates and kaon ID efficiencies are due to the statistical errors in the calibration procedures from the $K_s^0 \rightarrow \pi^+\pi^-$ and $\Lambda^0 \rightarrow p\pi^-$ data samples. Small discrepancies between the data and MC in the average multiplicities of quality tracks and the fraction of quality tracks passing the additional particle ID quality cuts are corrected for. The effects of the full corrections are included as systematic errors.

By far the dominant systematic uncertainty is due to the uncertainty in the K^+/K^- production ratio in B meson decays, which directly affects the analyzing power of the $K^{\pm}$ tag. We have adjusted the MC to match the ARGUS measurement [9] of average production rates and momentum distribution of kaons from B_u and B_d mesons. The $B \rightarrow K^+$ and $B \rightarrow K^-$ rates are varied independently

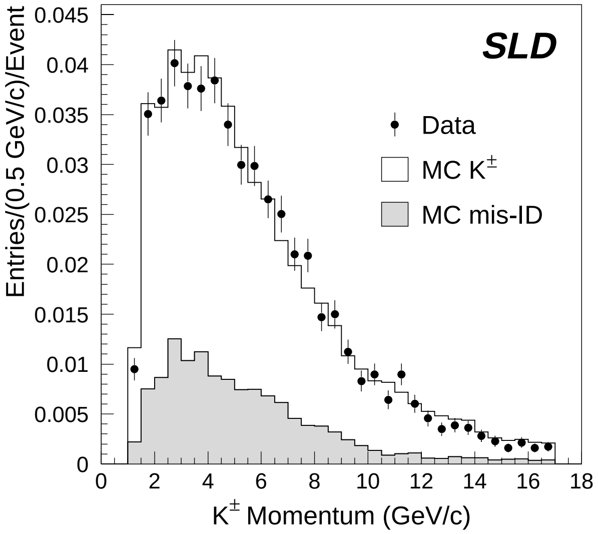

FIG. 1. Momentum distribution of selected B decay $K^{\pm}$ candidates.

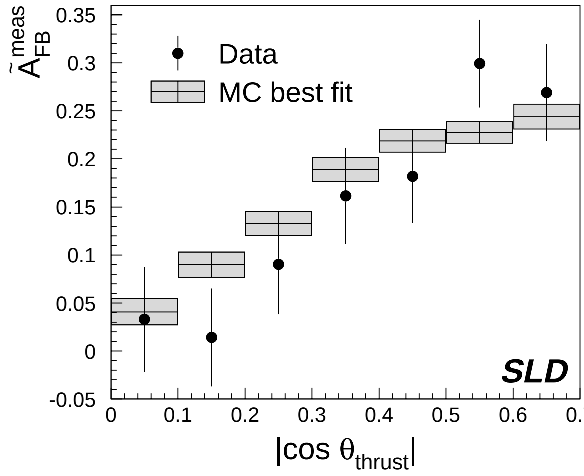

FIG. 2. Measured left-right forward-backward asymmetry for $b\overline{b}$ events as a function of thrust axis $\cos\theta$ for background-corrected data (points). The shaded boxes correspond to the best fit MC, where the vertical size of each box spans the $\pm 1\sigma$ MC statistical errors.

TABLE I. List of systematic errors on A_b.

Systematic source		$\frac{\delta A_b}{A_b}$ (%)
$\langle B_u + B_d \rangle \to K^+$ multiplicity	0.620 ± 0.040	∓ 4.7
$\langle B_u + B_d \rangle \to K^-$ multiplicity	0.165 ± 0.038	± 10.3
$\langle B_u + B_d \rangle \to$ proton multiplicity	0.055 ± 0.005	<0.1
Kaon momentum spectrum	$\cdots$	± 0.4
b fragmentation $\langle x_E \rangle$	0.718 ± 0.024	± 0.7
b fragmentation shape	$\cdots$	± 1.5
$b \to B_s$ production	$11.5\% \pm 1.8\%$	± 1.8
$b \to b$ baryon production	$10.0\% \pm 4.0\%$	± 1.9
$B_s^0 \to D_s^- + X$ fraction	$78\% \pm 10\%$	∓ 0.2
b baryon $\to c$ bayron $+ X$ fraction	$79\% \pm 10\%$	± 0.4
B_s lifetime	1.55 ± 0.15 ps	± 0.3
b baryon lifetime	1.10 ± 0.11 ps	± 0.1
charm decay $K^\pm$ and p yield	$\cdots$	± 1.1
Fragmentation $K^\pm$ production	$\pm 15\%$	± 0.1
b-tag $udsc$ background fraction	$\cdots$	± 0.1
A_c	0.67 ± 0.07	∓ 0.1
$g \to c\overline{c}$ production	$2.33\% \pm 0.50\%$	± 0.1
$g \to b\overline{b}$ production	$0.269\% \pm 0.067\%$	± 0.2
QCD correction uncertainties	$\cdots$	± 0.3
$\pi \to K$ mis-ID calibration	$\cdots$	± 0.7
K ID efficiency	$\cdots$	± 0.8
particle ID track selection	$\cdots$	± 0.2
MC Tracking efficiency	$\cdots$	± 0.7
MC statistics		± 0.3
Beam polarization	$77.2\% \pm 0.5\%$	∓ 0.7
Total systematic uncertainty	$\cdots$	± 11.9

according to the respective experimental errors, and the resulting changes in A_b are added in quadrature. This is a conservative estimate, as many systematic errors in the ARGUS measurement are common to the K^+ and K^-, and should cancel in the K^+/K^- production *ratio*, which is relevant for this measurement. The effects related to the $B_s \to K^\pm$ production uncertainty are relatively small, mainly due to the full B_s mixing, so that only total $K^\pm$ production rate matters. The small effects related to b-baryon decay uncertainties are due to the small direct kaon yield in b-baryon decays and also to the fact that many protons from Λ decays (which could fake a $K^\pm$ signal) are not selected as B decay candidate tracks.

The kaon momentum distribution shape uncertainty is estimated from the difference between two different tunings of the CLEO QQ B decay model which have either enhanced kaon sources from $B \to D\overline{D}X$ or $s\overline{s}$ production in W fragmentation. The b-fragmentation modeling is based on a phenomenological parametrization [15] of B hadron momentum distribution which provides a good description of data. The b-fragmentation systematic uncertainty includes the effect of a wide range of variation of the average scaled B hadron energy $\langle x_E \rangle$ as well as an alternative model with the Peterson fragmentation function [16] shape. The systematic uncertainty from kaon production in charmed hadron decays is estimated for charmed hadrons produced in B_s meson and b-baryon decays, and from $c\overline{c}$ background events, based on the Mark-III measurements [17].

The uncertainty in the $udsc$ background fraction is estimated as in our R_b measurement [13], and the effect on A_b is found to be very small. Varying R_b and R_c by their current measurement uncertainties yields negligible effects on A_b. The insensitivity to background fractions is due to the high b purity and the fact that the raw asymmetry of $c\overline{c}$ events has the same sign and similar magnitude to the $b\overline{b}$ events. The systematic error assigned to the QCD correction includes uncertainties in the second order QCD corrections and α_s, in the bias due to event selection criteria in the analysis, and the quark mass effect in the matrix elements.

In summary, we have performed a direct measurement of A_b from the left-right forward-backward asymmetry using the highly polarized electron beam at the SLC. This measurement demonstrates the effectiveness of a new technique of b quark charge tagging using identified kaons together with a high purity b tag. We obtain $A_b = 0.855 \pm 0.088_{\text{stat}} \pm 0.102_{\text{syst}}$, consistent with the standard model expectation of 0.935. It also agrees with other direct measurements of A_b [2] from SLD of $A_b = 0.911 \pm 0.045_{\text{stat}} \pm 0.045_{\text{syst}}$ using the jet-charge technique, and $A_b = 0.910 \pm 0.068_{\text{stat}} \pm 0.037_{\text{syst}}$ using the lepton technique [18] from the same data period. The resulting combined SLD result from the 1993–1995 data is $A_b = 0.905 \pm 0.051$. This is also consistent with the indirect measurement average of $A_b = 0.887 \pm 0.023$, derived from the preliminary combination of the LEP A_{FB}^b measurements, in conjunction with the measured A_{lepton} from LEP and the A_{LR} from SLD. The systematic uncertainties from our kaon tag A_b measurement are very different from other measurement techniques and will be significantly reduced in the future with the 4 times larger remaining SLD data sample, which will enable the analyzing power to be determined directly from the data.

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*Deceased.

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